DOI: 10.31897/PMI.2019.3.259

UDC 550.3

# Geological and Geomechanical Model of the Verkhnekamsk Potash Deposit Site

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Major accidents at OJSC Uralkali raised the question of the need for a detailed study of the geological structure of the Verkhnekamskoye potassium salt deposit, the identification of anomalous complex zones in the oversalt rocks and, above all, in the water-blocking layer (WBL).

The article proposes a method for isolating weakened zones in the WBL and potash reservoirs, based on the combined use of geomechanical (laboratory core tests) and geophysical (acoustic broadband logging in wells and surface seismic exploration) studies. It also describes the method of zoning of WBLand potash reservoirs on the physical and mechanical properties to obtain their specific values. This technique will help solve the most urgent problem of ensuring industrial safety in the development of the Verkhnekamskoye potassium salt deposit (the safety of the WBL).

The implementation of the proposed method is considered for the Romanovsky site of the Verkhnekamskoye deposits of potassium and magnesium salts. The research included 2D seismic explorations, physical and mechanical properties testing, and finding statistical dependencies between static and dynamic geomechanical parameters. Based on the processing of seismic materials and the obtained dependencies, a geological and geomechanical model of this area was created, and zones with different physicomechanical properties were identified.

***Key words***: seismic; geomechanics; geology; physical and mechanical properties; acoustic impedance

***Acknowledgment.*** The authors of the article express their sincere gratitude to E.K. Kotlyar, Chief Engineer of PJSC Uralkali, who initiated these studies, as well as to Chief Engineer of PJSC Uralkali A. Macheret for the constant support of this research.

***How to cite this article***: Kashnikov Y.A., Ermashov A.O., Efimov A.A. Geological and Geomechanical Model of the Verkhnekamsk Potash Deposit Site. Journal of Mining Institute. 2019. Vol. 237, p. 259-267. DOI: 10.31897/PMI.2019.3.259

**Introduction.** The geological feature of major world potash deposits is the presence of watered layers located directly above productive potash strata. The part of the rock mass, located between the potash strata and the water-bearing rocks, is called the water-blocking layer (WBL). In the Verkhnekamskoye potassium salt deposit (VPSD), the water-blocking layer is a part of an impervious section of the rock mass (thickness of 50-140 m), located between the mining area and the horizon containing low-mineralized water and having active water exchange with overlying freshwater horizons ranging from 150 to 350 m.

The anomalous features of geological structure of the water-blocking layer, which are hazardous and could lead to flooding of potash mines with oversalt waters, represent zones of development of hypogenic sylvinites and fractures, incomplete cutting of the water-blocking layer, development of dynamic varieties of rock salt, high-amplitude placative dislocations, and replacement of the sylvite with rock salt [4, 8].

**Formulation of a problem.** Ground, subsurface and underground methods and complexes of geophysics and geomechanics are used to identify anomalous zones in potash reservoirs and the water-blocking layer, through which over saline waters can penetrate mine workings [1]. The authors of the article propose an effective method for identifying zones with different physical-mechanical properties in WBL and productive potash beds, based on the combined use of geomechanical and geophysical approaches [2, 10, 12].

**Description of the proposed method.** The method consists in obtaining correlation dependencies between static and dynamic geomechanical parameters with the appropriate laboratory equipment, correcting the obtained dependencies based on the results of well logging, obtaining the longitudinal wave velocity and acoustic impedance distribution based on 2D and 3D seismic data processing and, finally, extraction using the obtained dependencies in the array of WBL and potash zones with different degrees of compaction. It is possible to obtain in any layer (at any point) of the

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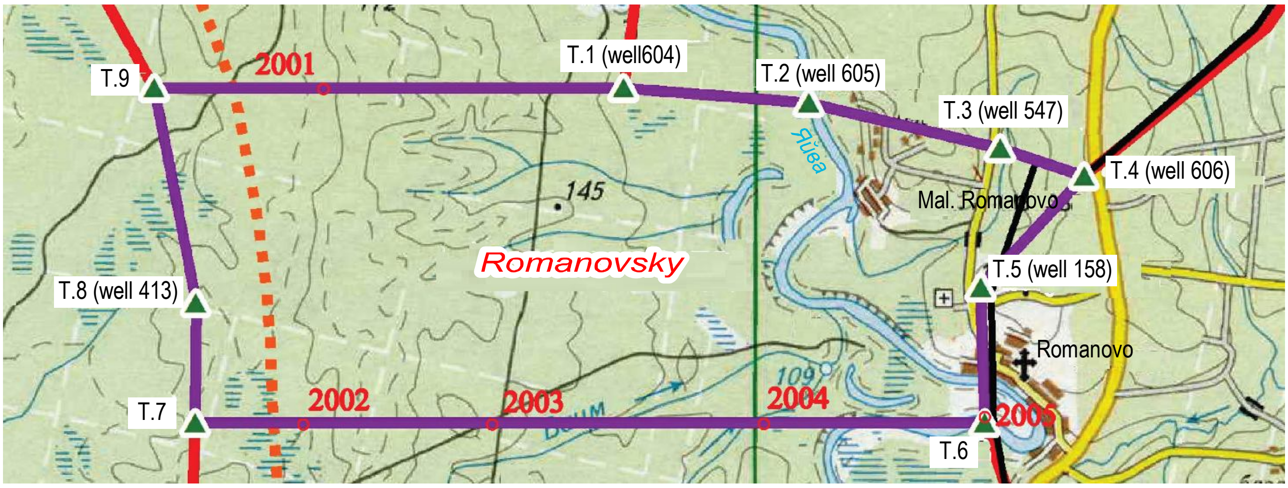


Fig.1. Map of the Romanovsky site

WBL the distributed values of such geomechanical parameters as uniaxial compressive strength, elastic modulus, Poisson's ratio, and several others. The subsequent solution of the problem of geomechanical modeling of the stress-strain state of the WBL involves the use of specific values of the physical-mechanical properties of the rocks composing the WBL and potash strata.

This method is based on geological information on the WBL structure, geophysical information obtained primarily from the results of 3D (or 2D) seismic processing, well geophysical surveys (GIS) and geomechanical dependencies derived from core tests. All this is the basis of the geological and geomechanical model (GGM) of WBL and potash reservoirs, which, in turn, is the basis for achieving the subsequent goal of obtaining reliable, reflecting the reality of deformation processes in WBL and potash reservoirs as a result of geomechanical modeling with different parameters of the development system.

It should be noted that geological and geomechanical models are widely used by the authors of this work and by foreign specialists for distinguishing compacted and decompacted zones in productive oil and gas condensate fields [6, 9, 11-13]. In this article, we consider the creation of a geological and geomechanical model of the Romanovsky subsoil VPSD along the line of salt-prospecting wells 2002-2003-2004-2005 (Figure 1).

The development of model consisted of the following stages:

1. The processing of a complex of geophysical studies to determine the dynamic values of the physical-mechanical properties of WBL using the borehole acoustic broadband logging method in wells 2004 and 2005.

2. The selection of core samples from the rocks of the salt layer in the wells of 2004 and 2005, the preparation of samples to determine their physical-mechanical properties.

3. The determination of the physical-mechanical static and dynamic characteristics of core samples on a PIK-UIDK/PL installation.

4. The establishment of statistical dependencies between static and dynamic geomechanical characteristics of rocks. Comparison with previously established dependencies.

5. The carrying out geophysical surveys using 2D seismic (12.5 km) along the line of 2002-2003-2004-2005 wells, obtaining velocity characteristics of the section and determining the dynamic characteristics of WBL rocks and potash strata along the line of these wells.

6. The creation of a geological and geomechanical model of a field site in specialized software, a forecast of the physical and mechanical properties of WBL rocks for wells 2002 and 2003 and a comparison of the results obtained with actual test results of core material from these wells.

To establish the statistical dependencies between the static and dynamic geomechanical characteristics of WBL rocks and the productive stratum, a core of 100 mm in diameter was selected from the 2004 and 2005 exploration wells of the Romanovsky site of the Verkhnekamskoye po-

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tassium salt deposit. The interval of core sampling ranged from 215 to 318 m in well 2005 and from 300 to 390 m in well 2004 and covered almost the entire section of the salt strata: the rocks of the layers of the transition suite, surface rock salt, sylvinite-carnallite and sylvinite zones.

Cylindrical samples with a ratio of height to diameter of 2:1 (60 × 30 mm) were made from the core material. A total of 145 samples were made (see Table).

**Number of tested samples**

| Rock | Compression | |
|---|---|---|
| | uniaxial | triaxial |
| Salt rock | 45 | 22 |
| Sylvinite | 45 | 17 |
| Carnallite | 12 | 4 |
| Total | 102 | 43 |

Studies of the geomechanical properties of core material were carried out at the installation of the Perm National Research Polytechnic University (PNRPU) PIK-UIDK/PL. The main attention in work was paid to tests on uniaxial compression (102 samples) [7] since this physical-mechanical parameter is of the greatest interest for engineering calculations [8]. To determine the parameters of the strength passport, triaxial stress state tests were also carried out (43 samples).

The general triaxial and uniaxial testing of samples for elastic and strength properties is as follows:

1) loading the sample up to reservoir conditions; hydrostatic stress field is taken as reservoir conditions for these samples ($\sigma_1 = \sigma_2 = \sigma_3 = \gamma H$);

2) holding the sample to stabilize the deformations $\partial \varepsilon_{vol} / \partial t = 0$;

3) measurement of longitudinal and transverse wave velocities $V_p$, $V_s$ in reservoir conditions;

4) experimental setup (uniaxial or triaxial compression);

5) increase in axial load with a constant velocity of axial deformation ($2 \cdot 10^{-4}$ $s^{-1}$) up to the destruction of the sample.

According to the results of the tests, dependencies were found:

• static modulus of elasticity in atmospheric and reservoir conditions from the dynamic modulus of elasticity, the velocity of the longitudinal wave, acoustic impedance;

• strength of uniaxial compression from the velocity of the longitudinal wave and acoustic impedance.

For example, Fig.2 presents the dependences of the strength of uniaxial compression on the velocity of the longitudinal wave. It was established that for rock salt, the dependence of the ultimate strength on the parameter. $V_p$ has a smaller correlation than for sylvinite; this is due to the considerable heterogeneity of the samples (presence of inclusions, layering, different grain sizes, etc.).

Separately, the dependence of uniaxial compressive strength was obtained for samples taken from the KrII layer (Fig.3). The uniaxial compression strength of productive layers is one of the

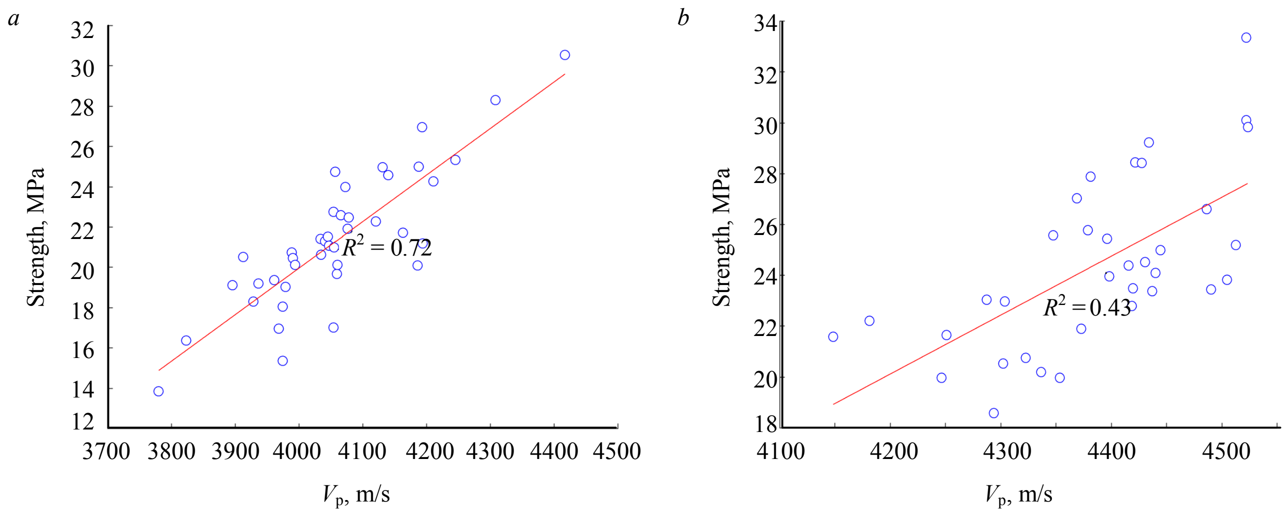


Fig.2. The dependence of the strength of the uniaxial compression of sylvinite (*a*) and rock salt (*b*) on the velocity of the longitudinal wave

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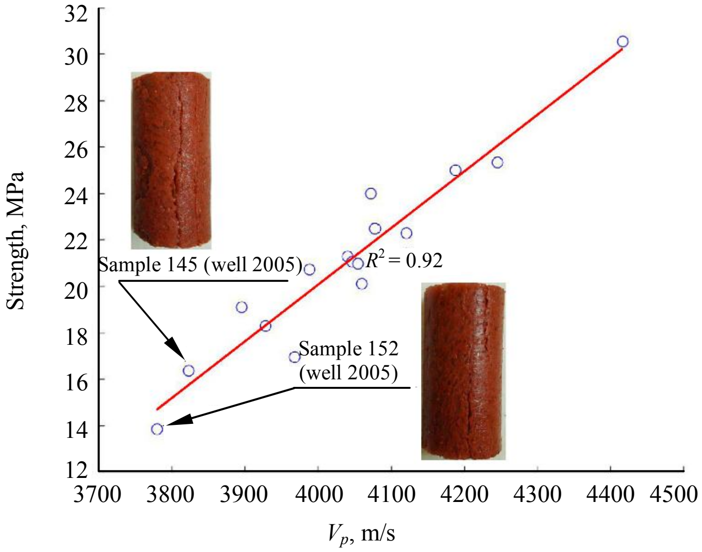


Fig. 3. Dependence of strength on uniaxial compression of samples sylvinite from the velocity of the longitudinal wave

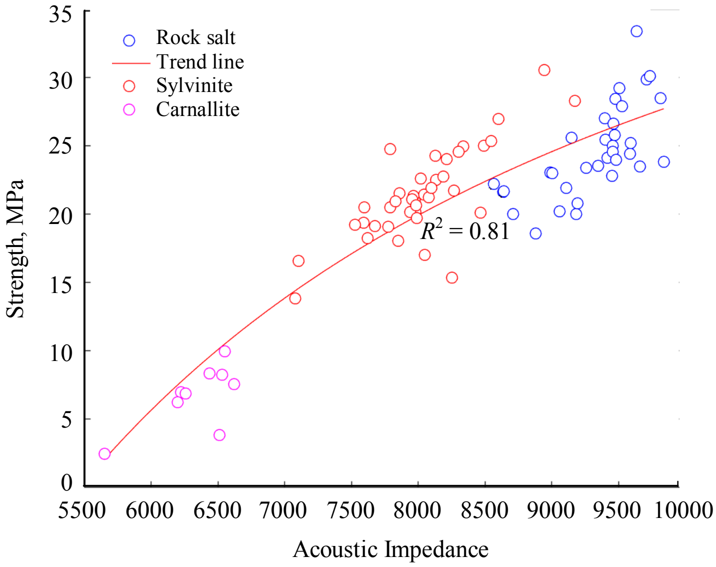


Fig.4. Dependence of uniaxial compression strength acoustic impedance

main physical-mechanical parameters that determine the degree of loading of the pillars and, accordingly, the parameters of the development system [8]. The coefficient of determination exceeds 0.9, which indicates a very high functional relationship of parameters. A higher correlation of parameters compared to the general dependence for sylvinite is associated with homogeneous samples obtained from the KrII layer.

The strength of the uniaxial compression of sylvinite KrII layer, as well as the velocity of ultrasound, varies widely ($\sigma_{cm}$ = = 13 ÷ 30 MPa, $V_p$ = 3800 ÷ 4400 m/s). Low strength values are associated with cracks in the samples (Fig.3), which was also reflected in the ultrasound velocity. High values of strength are explained by the presence of rock salt inclusions in the samples, which leads to an increase in the ultrasound velocity.

Acoustic impedance was used to unify the uniaxial compression strength into a single dependence for all types of rocks (Fig.4). This relationship was used in the construction of the geological and geomechanical model along the line of wells 2002-2003-2004-2005. To obtain mechanical properties along the length of the wellbore, static elastic and strength parameters were «linked» with logging data.

The next step was to solve the problem of determining the elastic dynamic characteristics of the salt and oversalt strata in the target area based on determining the velocities of the longitudinal and transverse waves $V_p$ and $V_s$ and volumetric density ρ. To solve these problems, 2D seismic materials were used that were made along the line of wells in combination with the results of geophysical surveys of wells 2004 and 2005.

The paper used one of several seismic survey methods - the method of reflected waves using the tool of a common depth point. The work was carried out along the line from west to east along with the wells 2002-2003-2004-2005 with one continuous profile, which allows continuous tracking of reflecting horizons along the specified line.

In the process of performing seismic exploration work, an explosive source of elastic oscillations was used - ammonite 6ZhV, charges of 200 g each, with an electric detonator. The explosions were carried out in wells with a depth of 1.5 to 2 m, with a diameter of 60-80 mm, charges in the wells were plugged.

***Processing of seismic materials***. The main purpose of processing seismic field materials was to obtain a seismic section with a high signal-to-noise ratio in the upper recording interval for further seismic inversion [3, 5]. The calculation of static corrections was made on the first arrivals of refracted waves. The level of reduction is selected by the top point of the relief.

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The processing included the amplitude attenuation using the gain factors calculated as a power function of time. For surface consistent amplitude correction, we first calculated the averaged curves of amplitude changes as a function of distance, and then the amplitude corrections for each point of explosion (EP) and point of reception (RP). To calculate the gain factors, a window was used that included the useful recording interval.

To effectively suppress low and medium-velocity noise-events, filtering was used in the F-K region, using a filter that is symmetrical with a wide fan to suppress (eject) the filter. The linear noise-event velocities for filter selection were estimated from seismograms of the total excitation point (TEP) and the total reception point (TRP). Filtration was applied to seismograms, both TEP and TRP together. Filtration was carried out before and after the deconvolution procedure.

To equalize the frequency spectrum of the seismic traces to compensate for the nonidentity of the excitation and reception conditions, a multifactorial, minimum-phase, surface-matched compression deconvolution was applied. To reduce the level of low and high-frequency noise, time constant band-pass filtering was applied in the frequency band $F_1$ = 6÷10 Hz, $F_2$ = 80÷90 Hz.

After clarifying the kinematic corrections, the automatic correction of static corrections was carried out several times. The obtained corrective static corrections made it possible to more fully take into account the effect of inhomogeneities of the upper part of the section and increase the reliability of the subsequent velocity analysis.

The final seismograms were corrected for residual phase shifts. Practice shows that the implementation of procedures for the correction of static and kinematic corrections is not enough for the complete rectification of the hodographs of the reflected waves. As a rule, time-varying phase shifts remain in the seismograms, which prevent in-phase summation of the useful signal. To improve the resolution of the seismic recording and eliminate residual random noise according to the summary data, such procedures as amplitude deconvolution and median filtering of frequency slices were applied. The final stage of processing was the migration procedure.

***Acoustic deterministic inversion.*** To solve the problem of determining the elastic characteristics (velocities of longitudinal waves $V_p$ and volumetric density ρ) of target strata in the interwell space (wells 2002, 2003, 2004, 2005), acoustic inversion technology was used. The results of the 2D seismic work in combination with the GIS results were used as the initial data. The preparatory stage included the analysis and adjustment of well logging data for wells to reference, simulate, and construct background models of longitudinal wave velocity and density.

The dynamic wavefield inversion algorithm included the following steps:

1. Evaluation of the seismic pulse shape carried out on the seismic profile in the time interval $\Delta T$ = 50÷300 ms.

2. A detailed stratigraphic referencing of well sections to seismic data. Model seismic traces calculated from GIS data were compared with seismic traces with control according to the position of the reference reflecting boundaries on the model and field traces. For the referencing and subsequent interpretation, four reflecting horizons (RH) were used, which were isolated and traced in a seismic wave field: RHPPACHKA – the top of the sediment of the transition suite; RHCarnal – roof carnallite seam; RH Silvin – the roof of the sylvinite layer; RHPodSilvin – sylvinite layer bed.

3. The reference impedance background model was built based on the velocity and density characteristics of four wells. The surfaces of the four main reflecting horizons served as the geometric frame of the model.

4. The inversion algorithm chosen by the test results (model based in the hardcon-straint modification) ensured the discrepancy between the model and real acoustic rigidity curves to 415 N·s/m$^3$ (±7 %).

5. Amplitude inversion was carried out based on an optimization approach, which consists of minimizing the objective function, which includes the reference errors between the observed and synthetic wave fields. Additionally, various restrictions are imposed on the allowable degree of deviation of the result from the reference model of the medium, ensuring the stability and spatial co-

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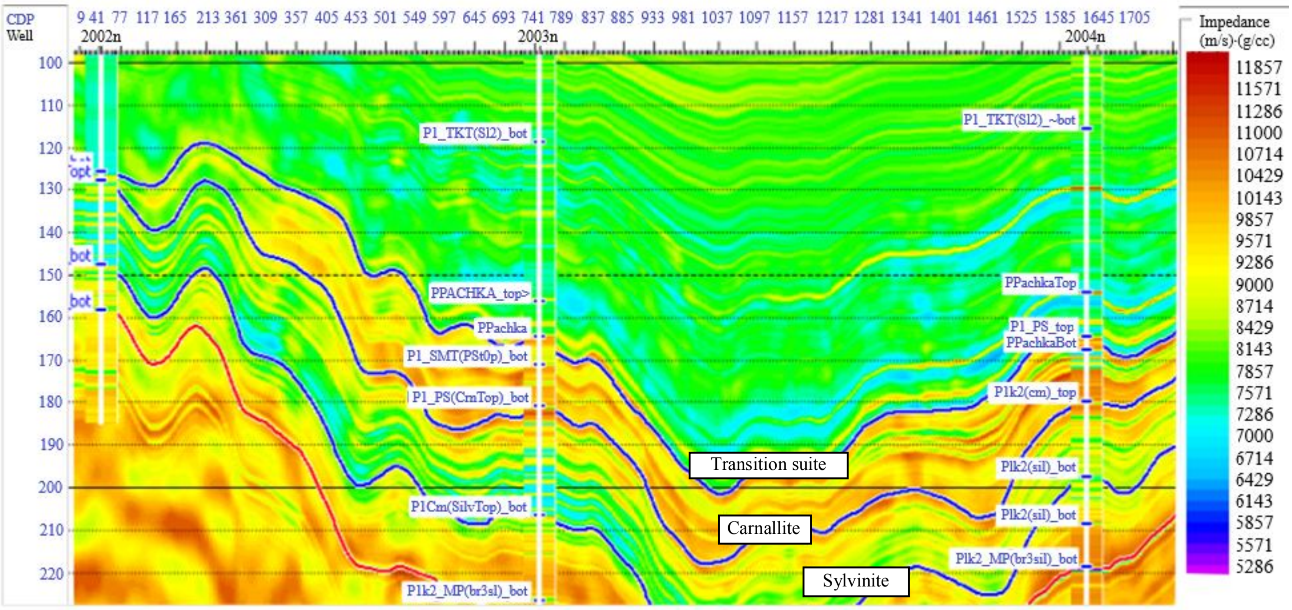


Fig.5. Comparison of the pseudo-acoustic impedance section with the GIS impedance in wells 2002, 2003, 2004

herence of the solution. As a result of the inversion, an acoustic impedance cube was obtained, corresponding to the optimal model.

The quality control of the inversion results showed a good correspondence between seismic and borehole impedance, which is demonstrated by a fragment of the final acoustic impedance section combined with color columns of acoustic impedance acoustic logging values (Fig.5).

**Discussion of the results.** The qualitative detection of weakened WBL zones complicating the mining of potash deposits is based on an analysis of the velocity characteristics of the wave field. The decrease in velocity values may be due to fracturing, lithological replacement by weaker rocks (clay, carnallite), tectonic disturbances, structural and lithological heterogeneities. For a quantitative assessment of the decrease in strength properties, the dependences of acoustic impedance on the physical-mechanical parameters of salt rocks were used (see Fig.4). These dependencies and the distributions of physical-mechanical properties obtained on their basis are, in essence, the geomechanical part of the geological and geomechanical model of WBL and productive potassium layers. Thus, based on the 2D acoustic impedance distribution obtained as a result of 2D seismic data processing, the distribution of uniaxial compression strength along the seismic survey line of wells 2002-2003-2004-2005 was established (Fig.6). Solid lines show the position of the roof of the transitional suite (TS), sylvinite zone (SZ), E layer, sylvinite-carnallite zone (CZ), KrII layer, KrIII layer, as well as marking clay (MC).

From the presented results, it can be seen that the stratification of the section is traced, alternation of rocks with low strength (carnallite, clay) and rocks with medium and high strength (sylvinite and rock salt). So, in the area of well 2002 carnallite seams with a strength of less than 8 MPa, clearly separated by rock salt beds with a strength of 22-28 MPa, are distinguished.

Based on the obtained results, we can estimate the substitution zones. So, in the section, you can trace the zone of replacement of carnallite sylvinite and rock salt in the area of wells 2004-2005 (Fig.6). For example, layer E in well 2004 has an average strength of 8 MPa, with distance from the well 2004 in the direction of the well 2005, the reservoir strength grows and at a distance of 800 m its value exceeds 15 MPa and further increases, which is associated with the replacement of weak carnallite rocks with stronger sylvinite and rock salt, which is confirmed by the results of core tests. The same analysis can be done for the rest of carnallite seams.

The result obtained allowed us to identify a weakened local zone in the KrII layer in the 2004-2005 well site (Fig.6). At 1700 m from well 2004 and on to well 2005, the formation strength drops to 16 MPa and below, which is most likely due to the increased content of clays in the reservoir and

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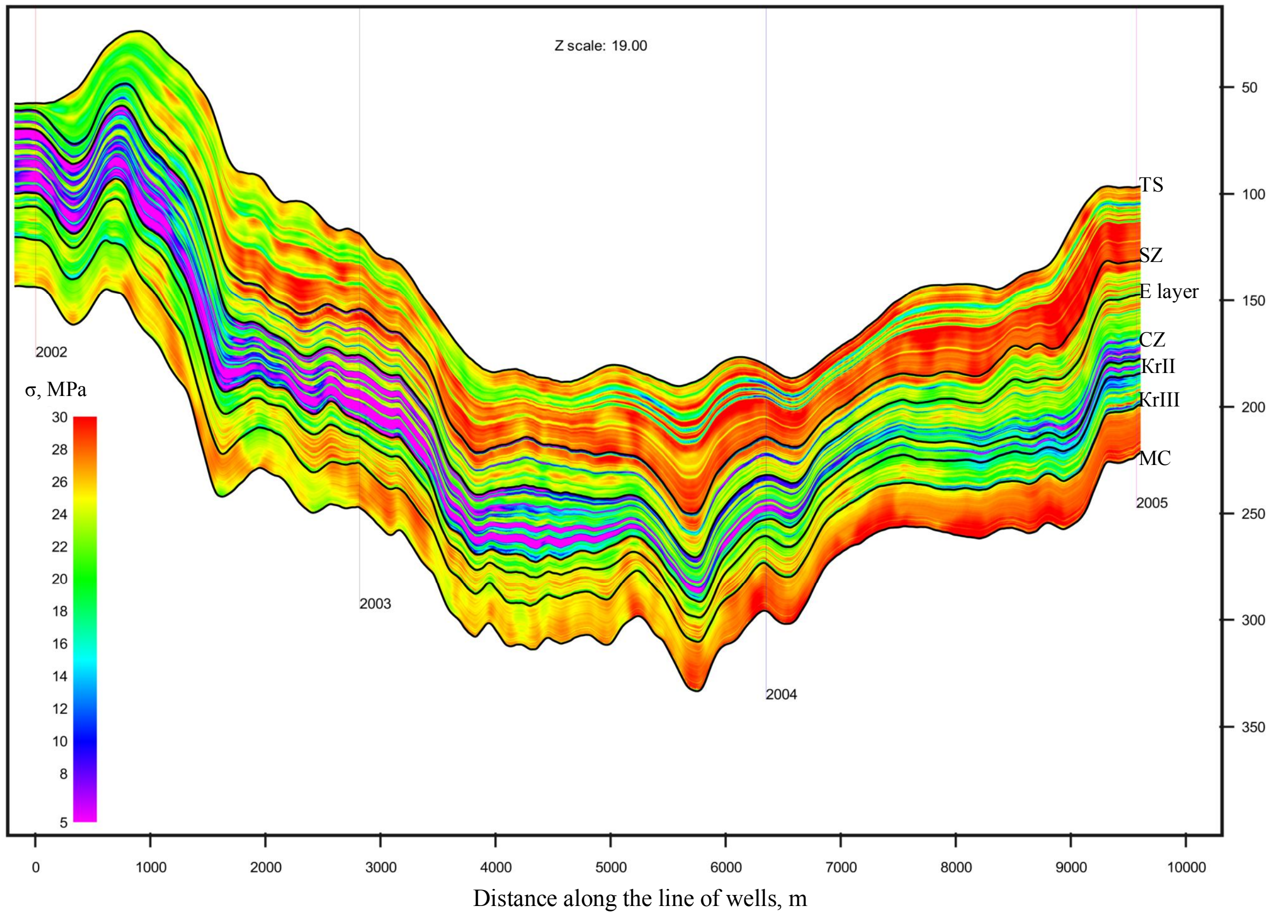


Fig.6. The distribution of the predicted strength for uniaxial compression along the line of wells 2002-2003-2004-2005

the presence of cracks. This result is confirmed by the core test since it is in well 2005 of KrII layer, low-strength specimens were obtained, and low values of acoustic broadband logging.

As part of independent verification of the proposed technology for isolating zones with different physical-mechanical properties, a comparison was made of the predicted values of the distribution of tensile strength for uniaxial compression in well 2002 and well 2003 with independent tests performed by specialists of the Mining Institute (MI UB RAS). Comparative data (Fig.7) show a good agreement of the predicted and actual values of the strength of the well 2002. The mean square error was ± 3.2 MPa with the scope of the actual values of strength from 2 to 28 MPa. Considering the accuracy of reference samples to a depth of 0.5 m (sometimes more), it can be stated that the predicted strength and strength obtained from the tests of the Mining Institute of the Ural Branch of the Russian Academy of Sciences are very satisfactory.

Analyzing the forecast for the well 2002, it can be concluded that the layers of the Z-I, E-Zh, V-G rock salt (26 MPa) have the greatest strength in the sylvinite-carnallite zone. In the remaining layers (layers Zh-Z, D-E, G-D), the strength values are slightly lower – up to 25 MPa. The minimum strength (less than 22 MPa) is confined to layers of interlayer rock salt (layers D, G). The strength of carnallite layers varies from 2 to 9 MPa.

As already noted, the decrease in strength in the layers of rock salt and sylvinite is associated with the presence of clay interlayers and inclusions of carnallite. So, for example, in the reservoir Zh-3, the strength drops from a maximum value of 24 MPa in «clean» rock salt to a minimum of 20 MPa in places where clays are present. On average, in the sylvinite zone, the strength of rock salt layers is less than in CZ. The minimum strength (less than 11 MPa) is confined to the layers of the layers KrI-KrII, A-KrI. The average calculated strength of the sylvinite layers is 20-23 MPa. The average value of the strength of the KrII layer is 20.7 MPa; for A layer it is 20.6 MPa.

The tests of the physical-mechanical properties of salt rocks from wells 2004 and 2005 of the Romanovskoe area allowed us to establish statistical relationships between the static and dynamic

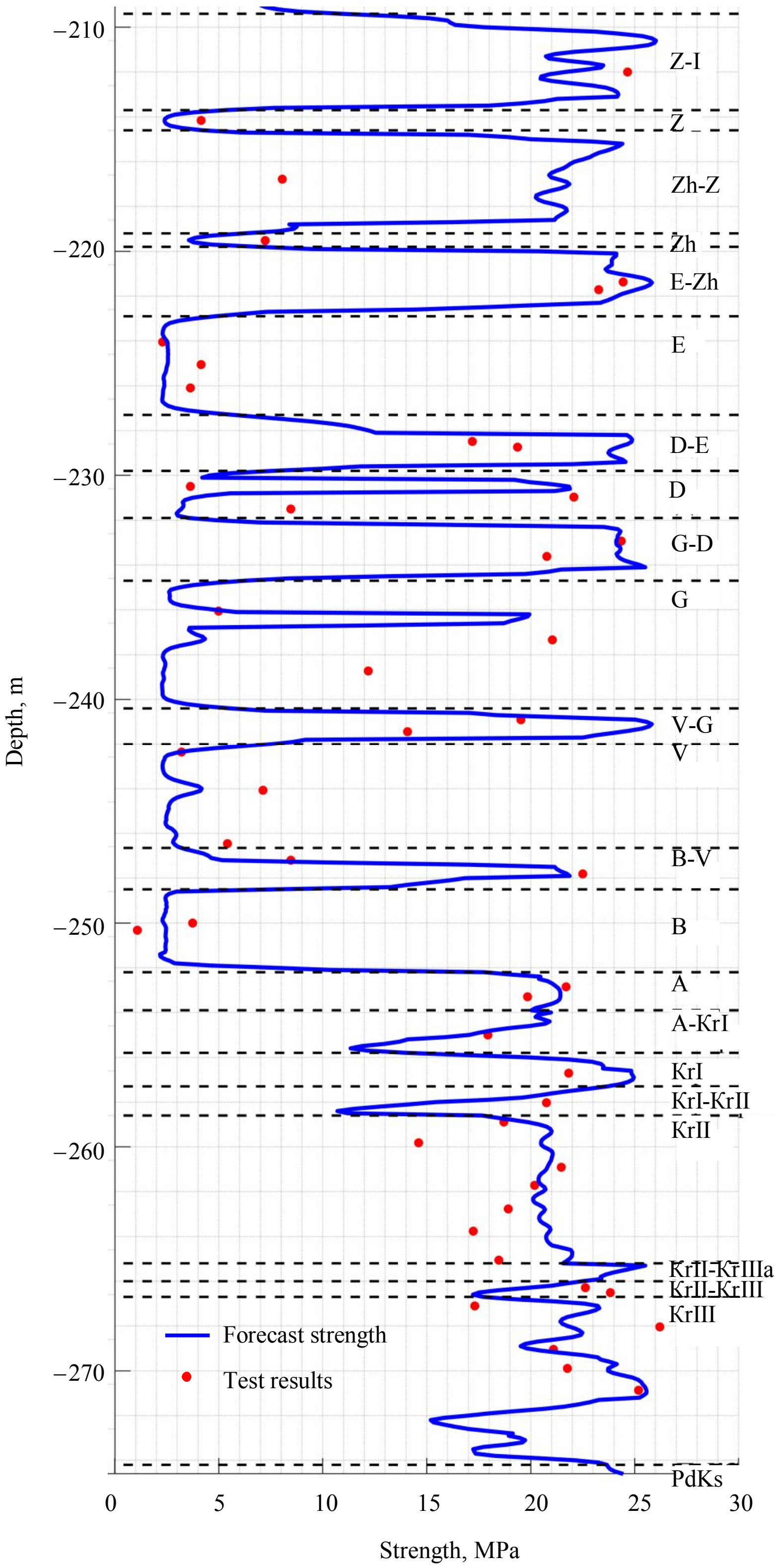


Fig.7. Experimental distribution (data from MI UB RAS) and predicted (PNRU data) strength in well 2002

geomechanical characteristics of salt rocks and confirmed the results of earlier studies by the authors [1, 2]. With reliable seismic information, the obtained dependences can be used to isolate zones with different physical-mechanical properties in the WBL and productive formations. At the same time, there is a high scatter of the values included in the resulting dependences of the parameters, which is explained by the heterogeneity of the sylvinite and carnallite rock mass, and, especially, rock salt. In this connection, the obtained dependences cannot be extended with a high degree of confidence to other parts of the VPSD. Dependencies are subject to further clarification and generalization.

Detailed processing of the results of 2D seismic to obtain elastic inversion allowed us to identify the main reflecting horizons in the interwell space and the roof of the main layers in the geological section. Based on seismic inversion, the distribution of acoustic impedance was found both in the well area and in the interwell space. Subsequent use of this parameter allowed us to establish the predicted distribution of compressive strength across the WBL and potash reservoirs in 2002 and 2003 wells. An independent comparison of the predicted strength distribution with the results of determining this parameter performed by the MI UB RAS showed their qualitative and quantitative convergence. All this suggests that the previously proposed method of allocating zones in the WBL and productive potash beds with different physical and mechanical properties is workable.

Based on the established connection of acoustic impedance with strength, zoning of the geological section along the line of wells 2002-2003-2004-2005 was performed by strength properties. It has been established that in the section along these wells there are no clearly defined broad zones of rocks with significantly weakened strength properties. At the same time, a local zone with weakened strength properties is present in the KrII layer in the 2004–2005 well site.

**Conclusions**. The working capacity of the previously proposed method for isolating weakened zones in WBL and productive potash beds, based on geomechanical and geophysical studies, has been confirmed. Its use is recommended both at the design stage of mining operations and at the development stage for a non-standard situation to obtain real physical-mechanical properties of a deforming rock mass and their application in geomechanical modeling. The use of the proposed solutions will allow not only significant progress in solving the problem of WBL safety but also optimize the parameters of the development system and increase the extraction of mineral resources.

It should also be noted that the proposed method of isolating zones with different physical-mechanical properties in the rock mass, based on the integrated use of geo-physical and geomechanical methods, can be used in almost any mineral deposit where there is a problem of industrial safety related to hazardous zones of the rock mass.

**REFERENCES**

1. Baryakh A.A., Sanfirov I.A. The system of integration of geomechanical and geophysical safety of underground mining. *Gornyi zhurnal*. 2005. N 12, p. 79-83 (in Russian).

2. Kashnikov Yu.A., Ermashov A.O., Shustov D.V. Creation of a geological and geomechanical model of a potash deposit with the aim of identifying zones with different deformation and strength properties in the water-blocking strata and potash reservoirs. Innovatsionnye napravleniya v proektirovanii gornodobyvayushchikh predpriyatii: geomekhaniche-skoe obespechenie proektirovaniya i soprovozhdeniya gornykh rabot: Sb. nauchnykh trudov / Sankt-Peterburgskii gornyi un-t. St. Petersburg, 2017, p. 309-319 (in Russian).

3. Kozlov E.A. Environment Models in Exploratory Seismology. Tver': Izd-vo GERS, 2006, p. 480 (in Russian).

4. Kudryashov A.I. Verkhnekamskoye potash salt deposit. Perm': GI UrO RAN, 2001, p. 429 (in Russian).

5. Ampilov Yu.P., Barkov A.Yu., Yakovlev I.V. et al. Almost everything about seismic inversion. *Tekhnologii seismorazvedki*. 2009. N 4, p. 3-16 (in Russian).

6. Kashnikov Yu.A., Shustov D.V., Yakimov S.Yu. et al. Development of the geological and geomechanical model of the tourney-Famennian object of the Gagarinsky field. *Neftyanoe khozyaistvo*. 2013. N 2, p. 2-6 (in Russian).

7. Rzhevskii V.V., Novik G.Ya. Fundamentals of rock physics: Moscow: Nedra, 1984, p. 359 (in Russian).

8. Guidelines for the protection of mines from flooding and the protection of underworked facilities at the Vernekamskoye potassium and magnesium salts deposit. Perm' – Berezniki, 2014, p. 130 (in Russian).

9. Fjaer E. Static and dynamic moduli of weak sandstones. Rock Mechanics for Industry. B.Amadei, R.L.Kranz, G.A.Scott P.H.Smeallie (eds). Rotterdam: Balkema, 1999, p. 675-681.

10. Hiroki Sone. Mechanical properties of shale gas reservoir rocks and its relation to the in-situ stress variation observed in shale gas reservoirs: Phd thesis. Stanford: Stanford University, 2012, p. 225.

11. Kashnikov Y.A., Achikhmin S.G., Shustov D.V., Yakimov S.Y., Kukhtinskii A.E. Reservoir Simulation of Part of Yurubcheno-Tohomskoye Oil Field Based on Geological Geomechanical Model: Program Book 9-th Asian Rock Mechanics Symposium. Bali, Indonesia, October 18-20th. 2016, p. 128.

12. Shustov D.V., Kashnikov Yu.A., Ashikhmin S.G., Kukhtinskiy A.E. 3D geological geomechanical reservoir modeling for the purposes of oil and gas field development optimization. EUROCK 2018: Geomechanics and Geodynamics of Rock Masses. St. Petersburg: CRC Press, 2018. Vol. 2, p. 1425-1430.

13. Zoback Mark D. Reservoir Geomechanics. Cambridge: University Press. 2007, p. 449.

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*The paper was received on 3 October*, *2018.*

*The paper was accepted for publication 12 January*, *2019.*